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CONCEPT FOR A

LARGE MASTER/SLAVE-CONTROLLED ROBOTIC HAND

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ABSTRACT

A strategy is presented for the design and construction of a large master/slave-controlled, five-finger robotic hand. Each of the five fingers will possess four independent axes each driven by a brushless DC servomotor and, thus, four degrees-of-freedom. It is proposed that commercially available components be utilized as much as possible to fabricate a working laboratory model of the device with an anticipated overall length of two-to-four feet (0.6 to 1.2 m). The fingers are to be designed so that proximity, tactile, or force/torque sensors can be imbedded in their structure. In order to provide for the simultaneous control of the twenty independent hand joints, a multilevel master/slave control strategy is proposed in which the operator wears a specially instrumented glove which produces control signals corresponding to the finger configurations and which is capable of conveying sensor feedback signals to the operator. Two dexterous hand master devices are currently commercially available for this application with both undergoing continuing development. A third approach to be investigated for the master control mode is the use of real-time image processing of a specially patterned master glove to provide the respective control signals for positioning the multiple finger joints.

INTRODUCTION

Objective

It is proposed to design and construct a large, anthropomorphic, master/slave-controlled, robotic hand. The envisioned device would be larger and more powerful than the human hand while possessing sufficient dexterity to closely mimic the fingering and grasping configurations of its human counterpart. The device has been assigned the

acronym, SLAVE² for, "Servomotor-Linked Articulated Versatile End Effector," reflecting the planned master/slave control mode and the use of an individual electric servomotor to drive each joint.

A rapid prototype R&D strategy utilizing off-the-shelf components wherever possible is proposed for the development of the SLAVE² laboratory prototype. A key goal of the strategy is to minimize development time and costs by eliminating long lead times for design and construction of individual components. The commercial availability of components including the electric servomotors and power transmission mechanisms to drive the individual finger joints will, thus, dictate size, weight, payload and finger length of the hand assembly. Based upon this consideration, it is anticipated that the initial working laboratory model will have an overall length of two-to-four feet (0.6-1.2 m) and an individual finger clamping force of 15-20 pounds (.067-.089 kN).

Previous Work in Robotics Hands and Grippers

Classification of robot hands may be based on mechanical characteristics. The basic criteria for classification is the number of "degrees of freedom" which the robot hand possesses. Degrees of freedom relates to the number of powered joints and the kinematics of the hand. The kinematics plus the geometry of the hand determine the envelope of the work space. Theoretically, the larger the number of degrees of freedom the more dexterous the hand and the more numerous the grasping patterns which can be achieved.

The current research in robotic hands has been motivated by extensive work in prosthetics and industrial grippers. In industry, grippers are designed for

securely grasping objects and the burden of maneuvering them is put on the robot joints where these grippers are attached. For various objects, different grippers with different finger shapes and actuation mechanisms are designed to be simple and durable [1]. For positioning small objects, industrial robots have been provided with small motion hands. An elegant example, is the Tokyo hand where three five-bar structures achieve 6-degrees of freedom to maneuver a triangular plate [2].

To improve the dexterity of the robot hands, computer controllers have been incorporated. These computerized controllers provide the potential of designing articulated robot hands with programmable and reconfigurable fingers for different applications.

In designing prosthetic devices, much of the work has focused on developing simple grasping systems. An example of a simple single degree-of-freedom prosthetic hand is the Utah hand where myoelectric sensing has been employed [3]. A more advanced prosthetic device employing force balancing mechanics to allow fingers to curl and settle around the grasped object is the Belgrade hand [4].

Dexterity is a key feature in designing robot hands. Thus multi-degree-of-freedom hand designs have been reported in recent years. These designs employ a wide range of actuating devices (e.g. pneumatic, hydraulic and electric servomotors) and force and tactile sensing. In particular, the dexterous robot hand developed at Japan's Electro-Technical Laboratory is a computer controlled 3-finger, 11-degree-of-freedom device able to grasp and impart controlled motions to rectangular and spherical objects [5].

Another remarkable design was the Stanford/JPL hand which has three, 3-degree-of-freedom fingers [6]. That design proved that three fingers are sufficient to grasp an object assuming that the object is held in the fingertips. That grasping technique is not very secure since efficient grasping requires that fingers curl around

objects and hold them against the palm. Also developed was a hierarchical control system for commanding the fingers and object motions [7].

Using the shape memory alloy (SMA) technology, Hitachi has combined the actuator and transmission into one mechanical element [8]. The Hitachi hand is kinematically similar to the Tokyo hand. The slow response time, high power consumption, and actuator fatigue failure are three significant problems with this hand design.

The most complex mechanical hand is the UTAH/MIT hand [9-11]. The current design has a total of 17 degrees of freedom and consists of three, 4-degree-of-freedom fingers and one, 4-degree-of-freedom thumb. The hand presents a major success in designing a very complex mechanical system and in the high performance achieved. The major drawback is the high power consumption and the large amount of computation resources (3-5 Motorola 68000 microprocessors).

Common to all of these systems are a number of major design issues. The number of digits affect the effectiveness of secure grasping while more joints broaden the range of grasping capabilities. One of the major issues in designing dexterous robot hands is the choice of actuation and transmission mechanisms. To avoid excessive weight, actuators are often located away from the hand and a variety of transmission schemes are utilized. In particular, cables routed through flexible conduits and Kevlar composite flat ribbons passing over pulleys are used.

As indicated, dexterous hand designs are characterized by the kinematics, actuators, and transmission mechanisms. In the following section, these key factors will be discussed briefly for the proposed SLAVE² dexterous hand.

PROPOSED ROBOTIC HAND DESIGN

Kinematics

A mechanical hand configuration possessing four fingers and a thumb is

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contemplated. Each of these five members will have four joints or degrees-of-freedom. More specifically, for each finger/thumb member three joints would provide flexion and extension (and possibly hyperextension) and a fourth joint would allow abduction and adduction. This would give the hand a total of twenty degrees of freedom and provide sufficient dexterity to closely replicate the gripping and fingering actions of a human hand.

Actuators

Each of the twenty joints is to be directly driven by an independent DC servomotor and integrated speed reducing mechanism. The brushless DC type of servomotor duplicates the external performance of a conventional DC motor without utilizing a commutator or brushes. This is possible because solid-state electronic switching replaces the conventional brush commutation switching process. A second major difference is that the wound member, or armature, reverses its role and relative position from rotor (rotating member) and inner component in the conventional DC motor, to stator (stationary member) and outer component in the brushless motor. These two differences lead to a number of significant advantages from the brushless DC motor [12-13]:

1. No brushes to wear out: increased reliability, reduced maintenance requirements.
2. No commutator bars to oxidize: ability to sit idle for years without loss of performance.
3. Absence of brush arcing: safer in the presence of fumes, dust, paint spray, etc.
4. Speeds up to 80,000 RPM are practical.
5. Less radio-frequency interference.
6. Easier cooling of windings with fins or cooling jacket: extended operating range.
7. Smaller diameter, more compact.
8. Reduced inertia: increased acceleration and improved control.

Although practical brushless DC servomotors are a relatively recent development triggered by advances in

solid state electronics and permanent magnet technology, units are now available from a number of major manufacturers. Included in this category are suppliers such as Inland, Moog, Litton Clifton Precision, Fanuc, Indramat, Mavilor and Ejectorcraft.

Power Transmission

Electric motors characteristically produce relatively low torque in the low speeds range. This is true as well for brushless DC motors, and preliminary calculations indicate that torque multiplication (or speed reduction) rates in the area of 200:1 will be required to achieve the desired robotic hand strength. To meet this requirement, the patented harmonic drive gearing device available from the Harmonic Drive Division of the Emhart Machinery Group, Wakefield, MA, has been tentatively identified. The harmonic drive has three simple, concentric components:

- 1) a rigid circular spline with internal gear teeth, the outermost component which is a non-rotating member for speed reducing applications;
- 2) a non-rigid "flexspline" with external gear teeth, the intermediate member of the assembly serving as the output member for speed reducing applications;
- 3) the elliptical wave generator, the innermost of the concentric components serving as the input member with its elliptically shaped inner bearing race and ball bearings rotating within an outer bearing race of the "flexspline" output member.

The fact that the outer rigid circular spline has two more teeth than the mating "flexspline" results in a relative angular motion between these two components equal to the spacing of two teeth for each complete rotation of the elliptical wave generator. With the circular spline rotationally fixed, the "Flexspline" will rotate in the opposite direction to the input at a reduction ratio equal to the number of teeth on the "Flexspline" divided by two. A detailed explanation of these operating principles is given in the "Harmonic

Drive Designers Handbook" [14] along with load and accuracy ratings, operating life expectancies and installation and servicing guidelines,

The unique design of the harmonic drive yields the following advantages for robotics applications:

1. Exceptionally high torque and power capability in a small package.
2. Essentially zero backlash.
3. Efficiencies as high as 90%.
4. Ratios as high as 320:1 in a single reduction with much higher ratios achieved by compound stages.
5. Concentric input and output shafts.
6. No radial loads since torque is generated by a pure couple; this simplifies the supporting structure requirements.

Drawbacks of the harmonic drive are that it is relatively compliant exhibiting a soft windup characteristic in the low torque region, and that it produces a small, sinusoidal positional error on the output. This error varies inversely with the pitch diameter at a predominant frequency of twice the input speed. Additionally an amplitude modulation typically occurs twice per output revolution.

Electronic Programmable Controllers

With the many degrees of freedom required for dexterous robot hands, the problem of control and demand on computing escalates. The simplest approach is to use a local control loop for each joint. However, for precise motion control, a coordinated motion for fingers and digits becomes a must for an efficient design.

For master-slave operation, where the coordination is achieved by the action of a human in the loop, the coupling between the fingers is neglected. Currently, a number of high performance servomotor controllers are commercially available. These controllers are designed to be programmable and installed in personal computers.

DEXTEROUS HAND MASTERS

The proposed master/slave control mode

calls for the operator to wear a specially instrumented dexterous hand master. This device must produce control signals capable of directing the servomotor actuators of the robotic slave hand into correspondence with the respective positions of the human operator's hand joints. Plans call for consideration of three different dexterous hand masters to carry out this control function. Two such devices, the A. D. Little "Sarcos Dexterous Hand Master" and the VPL Research "DataGlove" are currently commercially available though both are undergoing continuing development. Their application will be discussed briefly in the following paragraphs together with a third approach utilizing real-time image processing of a special optically patterned master glove.

A. D. Little Sarcos Dexterous Hand Master

Arthur D. Little, Inc. of Cambridge, Massachusetts [15] offers a Sarcos Dexterous Hand Master. The device utilizes mechanical linkage assemblies secured to the individual finger digits by means of flexible ring-like bands. Built-in hall effect potentiometers translate the various linkage motions into electrical signals which can be correlated to the individual finger joint movements.

The linkages are constructed chiefly of aluminum, non-magnetic stainless steel, and delrin. A stainless steel hand clip is used to fasten the device to the hand. Special provisions include spring loading of the ring-like finger bands to maintain proper positioning even though the fatty tissue of the finger changes shape as the joints flex; and, "passive pivots" perpendicular to the joint bending axes to accommodate the non-parallel joint axes commonly resulting from crooked fingers.

Currently, up to twenty human joints motions can be monitored with a resolution of one-half degree over their full range for flexion or ab/adduction. Each channel is sampled 100 times per second to provide for real time finger configuration data. Accuracy of

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positioning and repeatability are said to be strong points of the A. D. Little hand master.

VPL DataGlove

VPL Research of Redwood City, California markets the DataGlove [16-18], an ingenious glove-like dexterous hand master that senses hand gesture position and orientation in real time. The device utilizes fiber-optic cables sandwiched between a stretchable inner glove and a cloth outer glove.

Each joint motion to be detected requires a separate fiber-optic cable laid in a parallel path running across the joint and looping back so that both free ends are anchored in an interface board mounted near the wrist. At one end of the cable is a light emitting diode source and at the other a phototransistor. The segments of the cable which rest over the joint are specially treated so that the light escapes when the joint is flexed. The greater the degree of bending, the greater is the loss of transmitted light. This effect can be detected by the phototransistor and calibrated to provide angular measurements with a resolution of one degree. A data acquisition rate of 60 times per second is used.

An additional feature on the DataGlove Model 2 System is a high resolution, 3D, magnetic digitizing device which provides for 6-degree-of-freedom (three translation and three rotation coordinates) tracking of the absolute position of the hand. This tracking device, produced by Polhemus Navigation Sciences Division of the McDonnell Douglas Electronics Co., is designated as the "3SPACE Isotrak."

It should be noted that VPL Research has recently developed a counterpart of the DataGlove hand master called the DataSuit which provides configuration data for the entire body.

Optical Pattern Hand Master

A third method suggested for the master control mode is the use of a master glove imprinted with a special color-

coded optical pattern. In this approach, the respective control signals for positioning the multiple finger joints would be extracted from the glove image. Potentially, the required glove could be lighter, better fitting, less cumbersome, and less expensive than either the A. D. Little Sarcos Dexterous Hand Master or VPL DataGlove. The authors are not aware of any commercially available devices of this nature or any researchers who have applied this approach to date.

Nevertheless, the continuing gains in computing speed which are being achieved by parallel processing may make this a viable approach for mimicking the relatively slow, four-to-five hertz, action of the human hand. To achieve real time performance, however, while compensating for factors such as extraneous light or the masking effect of hidden fingers, special treatments might be required. For example, consideration might be given to the application of neural networks by which the system could be trained to quickly recognize specific finger configurations, or to the use of special image enhancing techniques such as the eigenimaging technique [19-20].

APPLICATIONS

The proposed SLAVE² approach has attracted preliminary support from the National Aeronautics and Space Administration (NASA). The device would serve as a laboratory model to develop end effector technology for Space Shuttle servicing and Space Station construction, servicing and repair operations. Tentative plans call for the construction of two similar models, one for study by the Kennedy Space Center (KSC), and the second for the Jet Propulsion Laboratory (JPL).

The KSC SLAVE² hand will be designed for installation on the IRB-90/2 Anthropomorphic Robot manufactured by ARI. The IRB-90 is capable of lifting approximately 200 pounds (90 kg) and holding it about ten feet (3000 mm) from its base with a repeatability of 0.04 inches (1 mm) under constant operational conditions. Further details of this system installed at the Robotics

Applications Development Laboratory (RADL) have been reported by V. L. Davis [21] of KSC.

The JPL model of the SLAVE² hand will be designed to attach to a laboratory work stand for testing and evaluation.

Anticipated commercial applications include handling of hazardous wastes, munitions, or large radioactive or chemically contaminated objects. Fire fighting, construction, demolition, disaster clean-up, and rescue operations might provide additional applications for a large dexterous end effector operated remotely under master/slave control.

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